

## AFOSR Final Progress Statement

- 1) **PI Name:** Donald P. Umstadter
- 2) **Grant/Contract Title:**  
  
(CONGRESSIONAL-ESP CODE KU) HIGH-ENERGY LASER FOR DETECTION,  
INSPECTION, AND NON-DESTRUCTIVE TESTING
- 3) **Grant/Contract Number:** FA9550-07-1-0521
- 4) **Reporting Period Start:** 06/21/2007
- 5) **End:** 06/21/2010
- 6) **Program Manager:** Howard Schlossberg
- 7) **Distribution Statement (as on SF-298): A**

A – Approved for public release

B – U.S. Government Agencies Only

C – U.S. Government Agencies and Contractors Only

D – U.S. Department of Defense and DoD Contractors Only

E – Department of Defense only

F – Further Dissemination only as directed by the Controlling Office

8) **Annual Accomplishments (200 words maximum):**

The central feature of the project was the development of a high-energy (30 J) high-power (petawatt) laser amplifier, which is seeded by an existing 100-terawatt, 30-fs laser system. This 2-pass, 10-cm aperture, Ti:Sapphire amplifier pumped by four high-energy (total of 100-J energy), high-repetition-rate (0.1 Hz), frequency-doubled Nd-Glass pump lasers, and a new, larger grating-based optical compressor, were installed in the Extreme Light Laboratory and successfully tested. The amplifier gain was measured, and shown to match the predictions of calculations based on an analytical model, which predict 1-PW peak power at maximum pumping. Transverse lasing was measured, and shown to be eliminated by the use of index-matching fluid surrounding the Ti:Sapphire crystal. The bandwidth of the amplifier was measured, and shown to be capable of supporting pulse compression to 25-fs duration. An optical protection system for the laser was also designed, installed, and successfully integrated—to prevent catastrophic damage to the amplifier by accidental bandwidth collapse.

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>21 SEP 2010</b>		2. REPORT TYPE <b>Final</b>		3. DATES COVERED <b>22-06-2007 to 21-12-2010</b>	
4. TITLE AND SUBTITLE <b>(Congressional -ESP code KU) High-energy laser for detection, inspection, and non-destructive testing</b>				5a. CONTRACT NUMBER <b>FA9550-07-1-0521</b>	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) <b>Donald Umstadter; Sudeep Banerjee</b>				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>University of Nebraska- Lincoln Department of Physics and Astronomy,Diocles Extrem Light Laboratory,Behlen Lab,Lincoln ,NE,68588</b>				8. PERFORMING ORGANIZATION REPORT NUMBER <b>25-0521-124-001 Final</b>	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) <b>University of Nebraska-Lincoln Office Of Sponsored Programs, 303 Administration BLDG, Lincoln, NE, 68588</b>				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) <b>AFRL-OSR-VA-TR-2011-0204</b>	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>The central feature of the project was the development of a high-energy (30 J) high-power (petawatt) laser amplifier, which is seeded by an existing 100-terawatt, 30-fs laser system. This 2-pass, 10-cm aperture, Ti:Sapphire amplifier pumped by four high-energy (total of 100-J energy), high-repetition-rate (0.1 Hz), frequency-doubled Nd:Glass pump lasers, and a new, larger grating-based optical compressor, were installed in the Extreme Light Laboratory and successfully tested. The amplifier gain was measured, and shown to match the predictions of calculations based on an analytical model, which predict 1-PW peak power at maximum pumping. Transverse lasing was measured, and shown to be eliminated by the use of index-matching fluid surrounding the Ti:Sapphire crystal. The bandwidth of the amplifier was measured, and shown to be capable of supporting pulse compression to 25-fs duration. An optical protection system for the laser was also designed, installed, and successfully integrated to prevent catastrophic damage to the amplifier by accidental bandwidth collapse.</b>					
15. SUBJECT TERMS <b>high-energy (30 J) high-power (petawatt) laser amplifier</b>					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>12</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			



**9) Archival Publications (published) during the reporting period:**

- V. Ramanathan, S. Banerjee, N. Powers, et al., "Submillimeter-resolution radiography of shielded structures with laser-accelerated electron beams," Phys. Rev. ST Accel. Beams 13, 104701 (2010)
- D. Umstadter et al., "Development of a Source of Quasi-Monoenergetic MeV-Energy Photons for Detection of Special Nuclear Materials," CP1099, Conference on the Application of Accelerators in Research and Industry, 20th International Conference , edited by F.D. McDaniel and B.L. Doyle (AIP, 2009), p. 606
- N. Cunningham et al., "High-energy Laser-accelerated Electron Beams for Long-range Interrogation," CP1099, Conference on the Application of Accelerators in Research and Industry, 20th International Conference , edited by F.D. McDaniel and B.L. Doyle (AIP, 2009), p. 638
- S. Banerjee et al., "Stable, monoenergetic 50-400 MeV electron beams with a matched laser wakefield accelerator," Proceedings of the Particle Accelerator Conference '09 (in press).
- S.D. Clarke et al., "Monte Carlo Characterization of a Pulsed Laser-Wakefield Driven Monochromatic X-Ray Source," Proceedings of the Conference on Technologies for Homeland Security 2009 IEEE Nuclear Science Symposium Conference Record N30-3, p.1998 W.J. Walsh et al., "Application of a Laser-Wakefield Driven Monochromatic Photon Source to Nuclear Resonance Fluorescence," Proceedings of the Conference on Technologies for Homeland Security 2009 IEEE Nuclear Science Symposium Conference Record N04-4, p.80

**10) Changes in research objectives (if any):**

No information

**11) Change in AFOSR program manager, if any:**

No information

**12) Extensions granted or milestones slipped, if any:**

Dec. 2008 1 year no-cost extension

Sept. 2009 6 month no-cost extension

Sept. 2010 6 month no-cost extension

**13) Attach Final Report (max. 2MB)**

**14) Attach SF298 Form**



# High-Energy Laser for Detection, Inspection, and Non-destructive Testing

Grant/Contract Number: FA9550-07-1-0521

---

Donald Umstadter (P.I.)  
Sudeep Banerjee

Final Report

3/21/2011

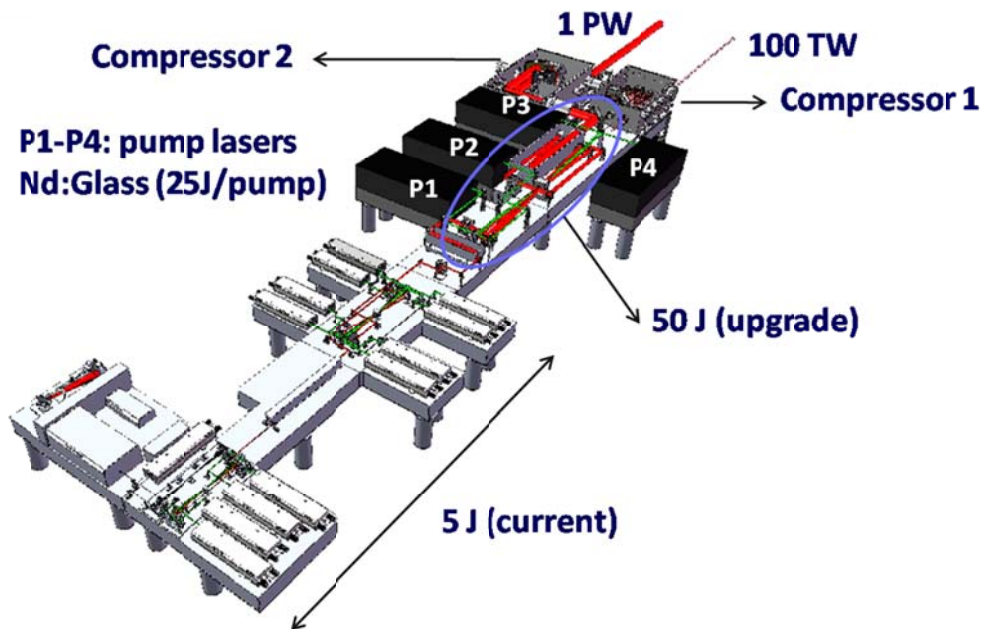
The University of Nebraska-Lincoln (UNL) has been upgrading its laser facility to increase its power rate by a factor of ten. The project comprised the construction begun in 2008 at the UNL Extreme Light Laboratory of a high-energy laser system that is capable of delivering a peak power of one petawatt, which will make it the highest combination of peak and average power in the U.S. This project also featured a reduction of the laser pulse duration. The project also supported applications of the laser, some of which are funded by other DoD agencies, to improve the quality of laser-driven electron beams and gamma rays, integrate radiation sources with suitable detectors and imaging techniques, and develop techniques for imaging through dense thicknesses of steel.

The central feature of the proposed laser upgrade project was the development of a petawatt high-energy laser amplifier, by the addition of a multi-pass amplifier and a pulse compression system for the amplified laser pulse. The layout of the complete laser system is shown in Figure 1. The original system comprised of an oscillator, stretcher, and 4 multipass amplifiers produced 5-J per pulse at 10-Hz repetition rate. The amplified pulse was compressed to 30-fs pulse duration in a standard two-grating pulse compressor and resulted in a peak power of >100 TW. The laser system has been upgraded to the 1-PW peak power level with an additional power amplifier and pulse compressor. The upgrade to the system consists of the following: (a) high-energy pump lasers, (b) power amplifier, (c) pulse compressor, and (d) diagnostics. The specifics of each are provided in detail below.

Once amplified and compressed, the light is transported to the target chamber and alignment assembly by means of the beam transport optical assembly. A characterization of the beam takes place in the diagnostic assembly, which is composed of photodiodes, ccd cameras, control computers, energy meters, spectrometer and autocorrelator, image plate and reader.

An optical protection system for the laser system, which prevents catastrophic damage to the amplifier by accidental bandwidth collapse, was designed, installed, and successfully integrated.

At the 100-TW laser power level, the energy of the laser-wakefield accelerated electron beam was increased to 0.8 GeV while maintaining the qualities of the lower energy beams (e.g., low angular divergence: 2 mrad). The electron and x-ray detection systems were cross-calibrated by means of an absolutely calibrated beam from a conventional accelerator.



a)

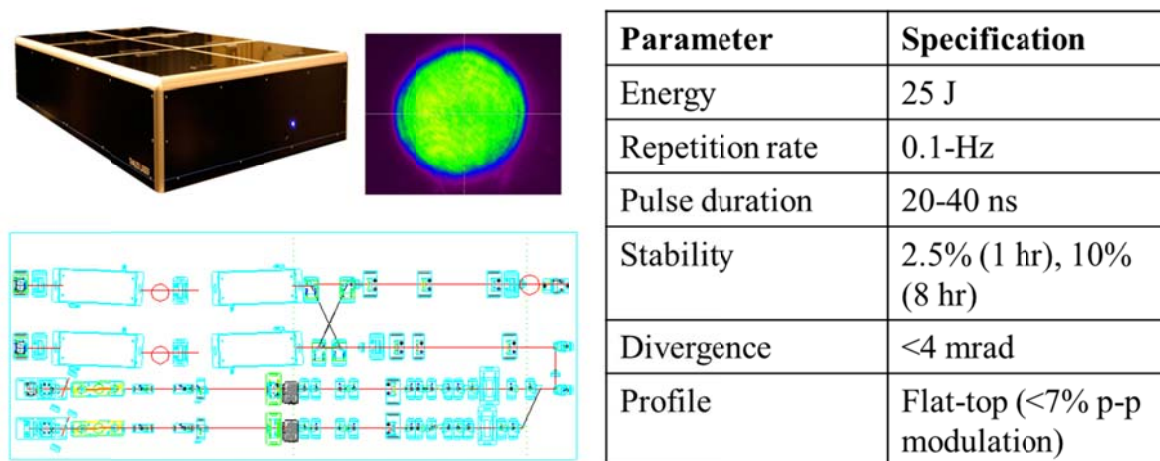


**Figure 1:** Layout of the Diocles laser system. The original system produced 5-J amplified pulses which were compressed to 100-TW peak power in compressor 1. The laser has now been upgraded to the 1 PW level by additional of an amplifier that boosts the amplified output energy to 50-J. The pulse is then compressed to 30 fs in compressor 2, and results in a peak power of 1 PW a) Schematic diagram of upgraded laser system, and b) photograph, of the amplifier with pumps and compressor chamber.

## System specifications

In order to produce 1 PW peak power, with compressed pulse duration of 30 fs, the required energy per pulse is 30 J (post-compression). With a typical compressor efficiency of 67%, the amplified pulse (pre-compression) energy is required to be 45 J. The front end of the system provides 5 J per pulse. Thus the final amplifier needs to have an output of 40 J per pulse. The efficiency of a standard multi-pass amplifier is ~40%. Based on these considerations, the pump energy required is 100 J.

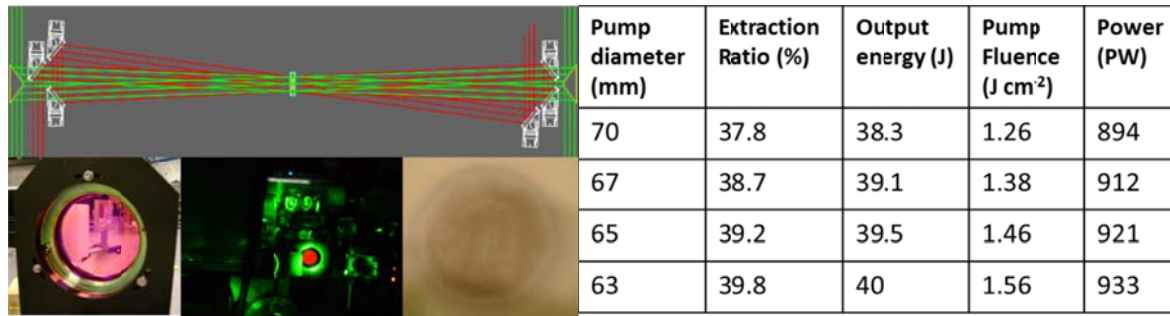
**Pump lasers:** In order to pump the power amplifier to boost the energy of the laser to 1 PW level, we acquired 4 high energy pump lasers (Atlas+) from Thales Laser, France. The pump lasers are based on Nd-glass technology and are designed to produce ~25 J of energy per pulse at 527 nm at a repetition rate of 0.1 Hz. The laser were designed and built to meet stringent specifications in order to ensure that the pump beam profile is of acceptable quality to pump a Ti:S amplifier. The pump lasers were shown to meet all the specifications excepting for spatial homogeneity of the output beam profile. The manufacturer of the system provided (at no-cost) a phase plate at the exit of the laser to smooth out the modulations and the spatial profile was shown to meet the specifications. The pump lasers meet stringent stability criteria which is critical for applications of the laser system in high-intensity experimental research.



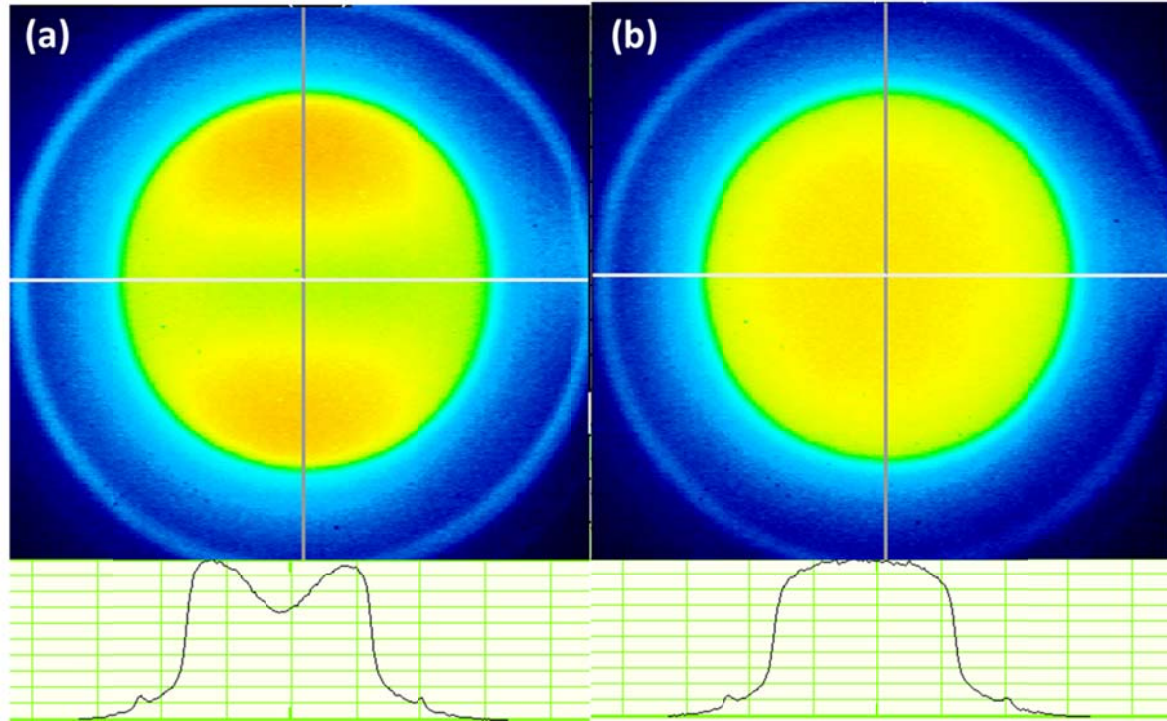
**Figure 1:** High-energy pump lasers for the PW amplifications system. The panel on the left shows the layout of each pump laser. It consists of two independent beamlets that are recombined into a single pulse at the output – a snapshot of the output beam profile is shown. The specifications for each of the four identical lasers are tabulated on the right.



**High-energy amplifier:** The 5-J beam from the front end of the system is amplified in a large diameter Ti:S crystal pumped by the Atlas+ lasers. The efficiency of the amplification process is more for a smaller beam size. The choice of beam diameter is made based on the damage specifications of the optical components in the amplifier chain. The stretching factor of the system was increased from 300 ps to 500 ps to account for the final beam aperture in the compressor. The amplifier system is a standard bow-tie configuration consisting of 3-passes. The 10-Hz beam from the front end of the system is coupled into the amplifier through an independent beamline that expands the beam to the correct diameter using a telescope arrangement. The repetition rate is stepped down to 0.1-Hz by use of an optical shutter and the pump beams are temporally synchronized to the infrared beam by the use of a “MASTERCLOCK” that is driven by the clock of the laser oscillator and ensures synchronization with a precision of ~100 ps. A schematic of the amplifier assembly and specifications for the amplifier system is shown in Figure 3. The infrared seed beam and the 4 beam beams are spatially overlapped on the crystal. At this time the beam size is 70 mm. This will be reduced to 65 mm to achieve maximum output. We have achieved 6-fold amplification in the final amplifier. The amplified energy matches the predicted gain based on calculations using the the Franz-Nodvik equations that model the operation of these amplifiers validating the design specifications for the amplifier.



**Figure 2:** Amplifier system for the PW upgrade. The amplifier is a 3-pass bow-tie configuration. The 4 high-energy pump lasers are synchronized with the infrared beam from the front end and are incident on a large aperture (115 mm) Ti:S crystal. The left panel shows the layout of the amplifier, the large diameter Ti:S crystal used for amplification, the amplifier system in operation and a burn of the high-energy amplified beam. The specifications of the amplified infrared pulse are shown on the right.

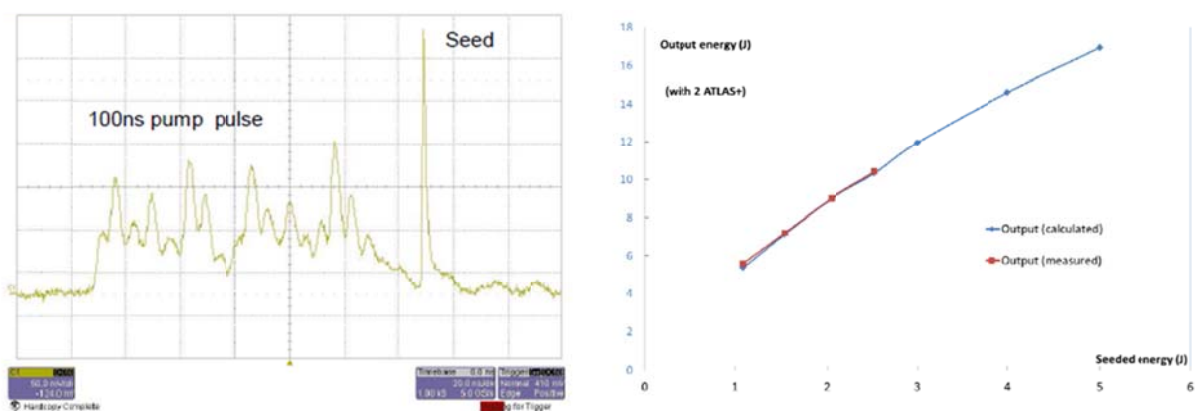


**Figure 3:** Transverse lasing measurements in the large diameter Ti:S crystal. The incident pump energy is 44 J and the fluorescence is measured on the same side as the crystal is pumped. (a) No index matching fluid on the periphery of the crystal; (b) with index matching fluid. The dip along the axis seen in case (a) is a characteristic signature of parasitic lasing, which is found to be suppressed in case (b) when Fresnel reflections from the interface are prevented.

A large diameter (115 mm) Ti:S crystal is used as the amplifying medium. Parasitic lasing due to the formation of a laser cavity by Fresnel reflections at the material interfaces of the gain medium is a major challenge in these amplifiers. We overcome this problem by use of an index matched fluid (refractive index = 1.76, the same as sapphire) at the crystal-air interface to prevent reflections into the crystal. The crystal is pumped at high-energy and absence of transverse lasing is demonstrated by imaging the fluorescence from the crystal surface. The results of this measurement are shown in Fig. 4. An on-axis dip in the fluorescence from the crystal surface is observed when no index matching fluid is used (Fig. 4 (a)). The fluorescence is spatially uniform with the use of the index matching fluid and shows no transverse lasing is present under normal operating conditions of the amplifier.

The repetition rate is stepped down to 0.1-Hz by use of an optical shutter and the pump beams are temporally synchronized to the infrared beam by the use of a “MASTERCLOCK” that is driven by the clock of the laser oscillator and ensures

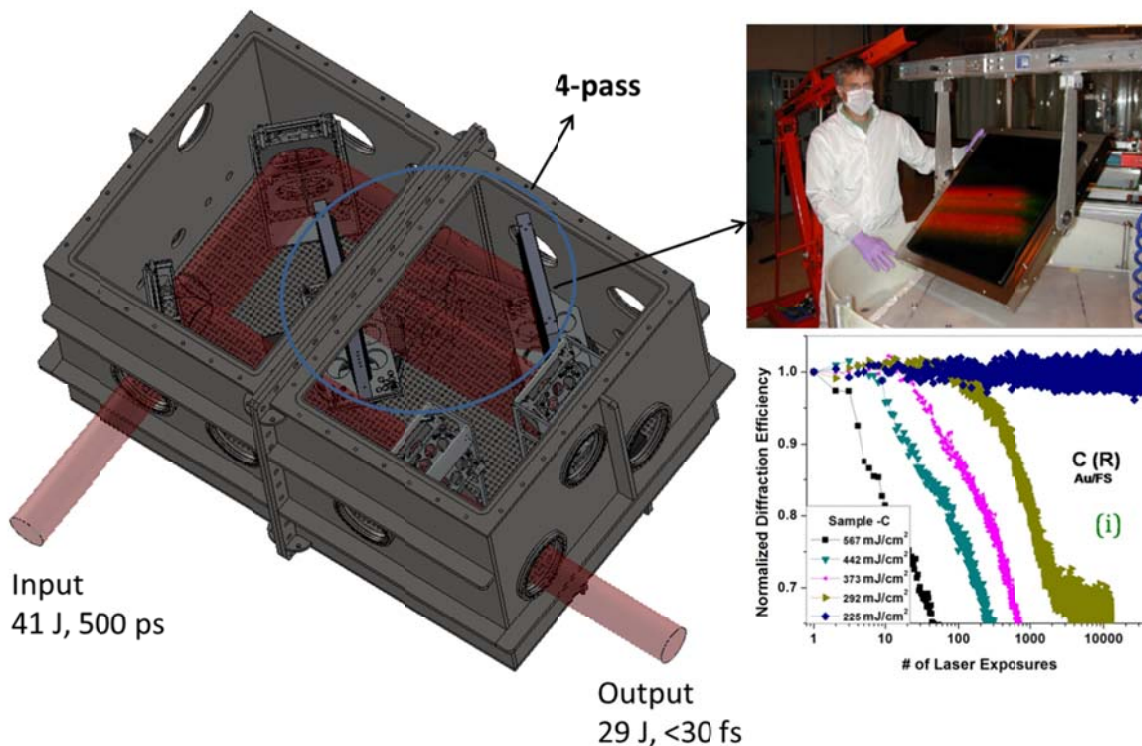
synchronization with a precision of  $\sim 100$  ps. A schematic of the amplifier assembly and specifications for the amplifier system is shown in Figure 3. The infrared seed beam and the 4 beam beams are spatially overlapped on the crystal. At this time the beam size is 70 mm. They are also temporally synchronized to ensure efficient amplification. The temporal profile of the combined pump pulse and the seed pulse is shown in Fig. 5. The pump pulses are delayed with respect to each other to account for the travel time of the IR pump beam in the amplifier and the build-up time. We have achieved 4-fold amplification in the final amplifier using two-pump beams. The output energy of the amplifier is measured as a function of seed energy. The amplified energy matches the predicted gain based on calculations using the the Franz-Nodvik equations that model the operation of these amplifiers as shown in Fig. 5. These measurements validate the design specifications for the amplifier. The beam size will be reduced to 65 mm in order to achieve maximum output.



**Figure 4:** Temporal sequence for pump beam and infrared seed beam in crystal for efficient amplification (left panel). The right panel shows the output of the amplifier as a function of input energy for fixed pump energy (blue curve). The red curve is based on model calculations.

**Pulse compressor:** The amplified beam with an energy of  $>40$  J is expanded a final time to a diameter of 175 mm. This is needed to operate within the damage threshold of the compressor gratings. The compressor is a standard 2-grating, 4-pass configuration as shown in Fig. 6. The gold-coated compressor gratings (dimensions 60 cm x 50 cm) were manufactured by LLNL. The amplified pulse with an energy  $> 40$  J and diameter of 175 mm enters the compressor as shown. It is then reflected off the gratings four times and gets compressed to a pulse length of  $<30$  fs. Each grating reflects  $>92\%$ ; hence the overall efficiency of the compressor is  $\sim 70\%$ . The compressor is equipped with motor

drives (rotation and translation stages) to control the alignment at the micron level in both position and angle.



**Figure 6:** Layout of PW compressor in a 2-grating, 4-pass geometry. The incident beam (40 J, 500 ps) is compressed to an output pulse of ~30 J, 30 fs and delivered to the target area. Panel on the right shows the large diffraction grating (60 cm x 50 cm) used for compressing the 175 mm diameter beam. The blue curve (bottom right) corresponds to an incident flux of 225 mJ cm<sup>-2</sup> and demonstrates that the compressor, will operation for the specifications of the system without any risk of damage to the optical elements.

Detailed measurements have been performed to verify that the grating meets the damage requirements in both long-pulse and short-pulse modes. The measurements show that a safe operating point for the grating is 225 mJ-cm<sup>-2</sup> at 0.1 Hz repetition rate (short pulse). The long pulse fluence on the grating is 180 mJ-cm<sup>-2</sup>, and the short pulse fluence is 130 mJ-cm<sup>-2</sup>, and both are significantly below the damage threshold.

**Diagnostics:** The upgraded laser system is equipped with an array of diagnostics for complete spatial, spectral and temporal characterization of the beam. The spatial profile of the high-energy beam in the amplifier is measured by taking burns on sensitive paper or imaging the beam profile using an optical system coupled to a CCD. A large bandwidth, high-dynamic range optical spectrometer is used to measure the spectrum of the amplified pulse before and after compression. The laser is equipped with a

spectral phase control system which is optimized to pre-compensate for gain narrowing in the power amplifiers and ensure the broadest spectrum at the output. This condition ensures that the pulse can be compressed to <30 fs. The energy of the beam is measured with standard, calibrated calorimeters. The pulse compressor output is optimized by using a second order autocorrelator to measure the temporal duration, an optical imaging system to correct for phase front tilt and a FROG device to measure and optimize the temporal phase of the beam.

### **How were awarded funds spent each year by objectives/outcomes?**

\$2,648,910 expended

Development of a high-energy laser amplifier: \$461,010

Year 1: Design of 2-pass Ti:Sapphire amplifier \$64,900

Year 2: Ordering of parts for 2-pass Ti:Sapphire amplifier \$89,000

Fabrication of compressor system \$460,000

Purchase of four high-energy, high repetition-rate, frequency-doubled Nd Glass lasers, delivered 2009 \$1,574,000

### **How did this project expand the laboratory's research and service capability or capacity?**

This project has enabled us to create five high-quality, high-paying, cutting edge jobs and hire three postdoctoral fellows and two technicians. It also has established UNL as an international leader in an innovative area of science – helping to put the State on the map as a player in high-tech research.

The high-energy laser system at the Diocles Extreme Light Laboratory at UNL is capable of delivering a peak power of 1 petawatt. This is critical to the enhanced development and performance of laser-driven radiation sources used for detection, inspection, and non-destructive testing. The ability of penetrating radiation sources to address these needs depends on several characteristics, such as energy, brightness, average power, and portability. All of these characteristics can be enhanced with improvements in the methods used to produce the radiation, and by enhancements to the drive lasers. All of the techniques will benefit from the new laser amplifier. The most immediate result will be the dramatic improvement of the brightness and quality of the laser-driven electron beams and x-rays, with applications for detecting cracks in aging critical components and detecting special nuclear materials through large thicknesses of

shielding. Thus, the project will have significant synergy with, and create leverage for, both the existing DARPA/AFOSR grant on hyperspectral radiation and DHS grant on SNM detection.

**Cumulative lists of people involved in the project:**

Donald P. Umstadter  
Sudeep Banerjee  
Kevin J. Brown  
Nathan Andrew Chandler-Smith  
James V. Kayser  
Suman Bagchi  
Chakra M. Maharjan  
Jun Zhang  
Kun Zhao  
Laila A. Gharzai  
Frank M. Lee  
Jeffrey A. Thomas  
Melissa D. Zephier  
Bertram M. Gay

**How has this funding been leveraged to continue the project or resulting research?**

- Defense Threat Reduction Agency, "Compact Source of Laser-Driven Monoenergetic Gamma-Rays" --\$2,982,685
- National Science Foundation, "High-Power Laser Science Collaboratory" -- \$1,825,345
- Defense Advanced Projects Agency, "Research and Development of a High-Power-Laser-Driven Electron-Accelerator Suitable for Applications, Phase II" -- \$899,823
- Domestic Nuclear Detection Office, Dept. of Homeland Security, "Tunable, monoenergetic x-ray source for identification of embedded SNM," Phase II-- \$899,000
- Domestic Nuclear Detection Office, Dept. of Homeland Security, "Tunable, monoenergetic x-ray source for identification of embedded SNM," Phase III-- \$1,133,848
- Congressional Add (PLUS, AFOSR), " High-Energy Laser detection, inspection, and non-destructive testing phase",-- \$ 4,759,860.00